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DC link Voltage Control during Sudden Load Changes in AC Microgrids

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Abstract— Parallel inverters in AC microgrids can achieve accurate power sharing using droop control. However, different grid line impedances will result in different transient power and thus different energy being delivered or absorbed by the inverters during sudden load changes. This might lead the DC link voltage to rise beyond the trip limit causing the inverter to shut down, which reduces the reliability of the whole microgrid. This paper investigates the effect of the mismatch in line impedances on the stability of the DC link voltage during a sudden load changes and proposes a scheme to control the DC link voltage during disturbances. Simulation and experimental results are presented to verify the efficacy of the proposed controller.

Keywords—droop control; inverters; DC link voltage

I. INTRODUCTION

A microgrid is a cluster of distributed generation (DG) units connected to a distribution network in order to maintain power supply to critical loads especially when the grid supply is not reliable or not available [1]. Power electronic inverters, connected in parallel, are used to integrate energy sources such as PV, wind and batteries into an AC microgrid, which can operate while connected to the grid (grid-connected mode) or as a stand-alone network (island mode).

Droop control as a power sharing technique has been extensively used and reported in the literature because it is easy, simple and inherently responsive when connected in parallel with synchronous generators [2]-[4]. In addition, it only uses local measurements, without the need for high speed communications between inverters and central controllers.

Small droop gains maintain good stability margins for a system as it provides lower bandwidth than that of the inner voltage and current regulation loops. It is capable of achieving accurate steady state active power sharing between paralleled inverters despite of mismatch in inverters filters components and line impedances. However, it does not guarantee equitable sharing of transient power. A large mismatch in line impedance will result in large differences in transient power being delivered or absorbed during disturbances such as sudden load changes. This leads to variations in the DC link voltage. If the DC link is interfaced by a second stage bidirectional DC/DC converter, in case of a battery system for example, the imported power can be absorbed and the DC link voltage can be controlled. However, if the DC link voltage is interfaced by a second stage unidirectional DC/DC converter, which is the case in wind, PV, micro-turbine, and fuel cell

systems, the absorbed power will cause the DC link voltage to rise, and if the voltage exceeds the trip limit the inverter will shut down, which reduces the reliability of the whole microgrid.

Many controllers have been proposed in the literature to improve the transient power response of paralleled inverters. Guerrero *et al.* [5] introduced power derivative-integral terms into conventional droop control to improve the dynamic response and to minimize circulating currents between paralleled inverters. Avelar *et al.* [6] proposed an extra phase loop to mitigate the transient response peak and to avoid overrating the inverter unit. In [7], a supplementary loop was proposed around the conventional droop control to stabilize the system while using high power angle droop gains.

Adaptive droop controllers were also proposed in [8] and an adaptive derivative term was added to the droop controller in [9] to decrease current overshoot and improve stability.

Although the abovementioned studies have focused on improving the transient dynamics of average power control, none has addressed the impact of transient power on the stability of the DC link voltage during disturbances such as load changes. Furthermore, none of these studies considered the effect of mismatch in line impedances on microgrid system damping.

This paper investigates the effect of line impedances mismatch on the stability of the DC link voltage during a sudden load change. A small signal state space model of a microgrid consisting of three inverters is used to analyse the system. A controller is proposed to control the DC link voltage during disturbances. Simulation and experimental results are presented to verify the performance of the proposed controller.

II. SYSTEM OVERVIEW

Fig. 1 shows a microgrid system composed of three DG units supplied by different energy sources. Each DG unit has a DC/DC converter and a DC/AC inverter with a DC link capacitor in between. The DC link voltage is regulated by a bidirectional DC/DC converter in the case of the battery system and by a unidirectional boost DC/DC converters in the cases of fuel cell and the gas micro turbine. The DC/AC inverter regulates the flow of power to the AC bus.

The droop mechanism is responsible for power control; it has an inner voltage controller to maintain the output AC voltage. Given that the output impedance is predominantly

inductive, the active power is proportional to the change of the phase angle between the inverter's output voltage and that at the point of common coupling (PCC) while the reactive power is proportional to the difference between the magnitudes of inverter and PCC voltages.

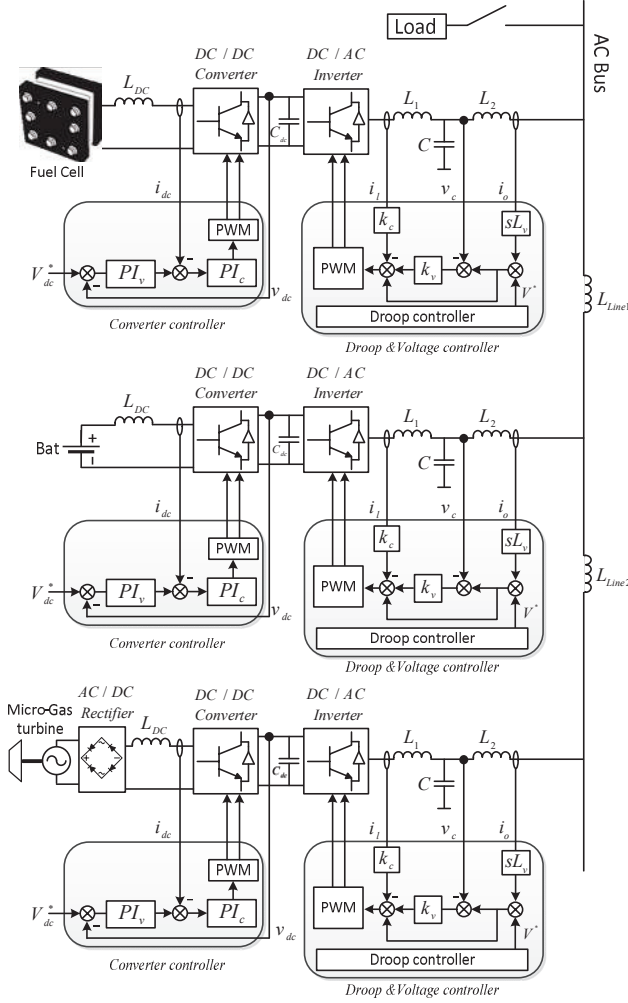


Fig. 1. Microgrid structure under study

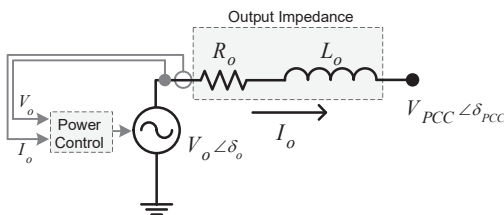


Fig. 2. Thevenin equivalent model of an inverter

Normally, there is no control link between the DC/DC converters and DC/AC inverters. The DC/DC converters are concerned with regulating the DC link voltage against any disturbances caused by the inverter side. The inverters are concern with managing the output power and voltage to satisfy the load demand. In the next sections, the study highlights cases where the DC link voltage can't be controlled because of this isolation between the controllers of the two converters.

The inner voltage loop is normally neglected in the modelling [9] because its response time is much faster than that of the outer droop control loop. In addition, the droop control is developed based on the steady-state analysis of power flow. As a result, the dynamics of power control loop shall be sufficiently slower than the DG voltage tracking dynamics. Therefore, each inverter can be modelled by its Thevenin equivalent circuit as shown in Fig. 2. The equivalent circuit model consists of an ideal voltage source, V_o , and an output impedance; $R_o + j\omega L_o$; which can be calculated as in [10]. The voltage source will be controlled directly by the droop equations.

III. DROOP CONTROL OPERATION

The frequency and voltage droops are described by (1) and (2), respectively as:

$$\omega = \omega_o - m_p P, \quad (1)$$

$$V = V_o - n_q Q, \quad (2)$$

where ω_o , V_o , m_p , and n_q are the nominal frequency, nominal voltage, frequency droop coefficient, and voltage droop coefficient, respectively. P and Q are the average measured output active and reactive powers, respectively. Average power is obtained from the instantaneous power p_{ins} using a low pass filter :

$$P = \frac{\omega_c}{s + \omega_c} p_{ins}, \quad (3)$$

where ω_c is the cut-off frequency, which is chosen to be much lower than the fundamental frequency to provide good filtration and frequency independence of the dynamics of the inner loops.

From Fig. 2, the instantaneous output active power related to the power angle of an inverter is given by

$$p_{ins} = \frac{V_o V_{PCC} \sin(\delta_o - \delta_{PCC})}{X_o}, \quad (4)$$

where V_o and V_{PCC} are the output voltages, δ_o and δ_{PCC} are the phase angles of the inverter and PCC node, respectively. X_o is the equivalent output reactance of the inverter where R_o is neglected.

By perturbing (1) we get

$$\Delta\omega = -m_p \Delta P. \quad (5)$$

By perturbing (4) and assuming constant V_o and V_{PCC} we get

$$\Delta p_{ins} = H_p \Delta\delta, \quad (6)$$

where $H_p = \frac{V_o V_{PCC} \cos(\delta_{eq})}{X_o}$, $\Delta\delta = \Delta\delta_o - \Delta\delta_{PCC}$, δ_{eq} is the

equilibrium point of the phase difference around which the perturbation is performed.

From (3), (5) and (6), the small signal model of the droop control loop can be represented by the block diagram of Fig. 3. By ignoring the LPF in Fig. 3, the transfer function that relates output power ΔP to the bus frequency $\Delta\omega_{PCC}$ is given by

$$\Delta P = \frac{-H_p}{s + m_p H_p} \Delta \omega_{PCC} \quad (7)$$

The DC gain in (7) equals $-1/m_p$ which means that if the inverters have the same m_p , they will all achieve equal steady state active power sharing. However, the transient response is determined by the pole $-m_p H_p$ which depends on both values of m_p and H_p . Therefore, equal m_p gains will not guarantee equal transient power sharing unless all H_p are equal, i.e., all X_o are equal. Thus, each inverter might have different damping depending on its location within the microgrid. It is important to take this into account when determining the droop gain m_p , which is normally chosen to satisfy the steady state condition such as

$$m_p \leq \frac{\omega_{\max} - \omega_{\min}}{P_{\max}}, \quad (8)$$

where ω_{\max} and ω_{\min} are the maximum and minimum allowable values of frequency and P_{\max} is the maximum output active power of the inverter.

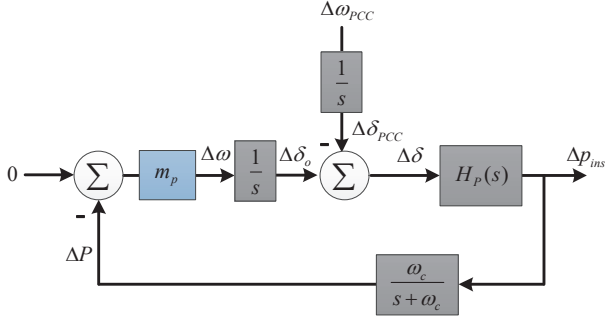


Fig. 3. Small signal model of the droop controller for one inverter

In Fig. 3, the frequency at PCC, $\Delta \omega_{PCC}$, is represented as a disturbance to the droop controller, which is mainly determined by the load. It is important to study the effect of varying load on transient power and hence the stability of the DC link voltage.

IV. DYNAMIC ANALYSIS

Unfortunately, the small signal model in Fig. 3 cannot be used for this study because a whole microgrid model needs to be developed in order to determine $\Delta \omega_{PCC}$. Thus, the microgrid model developed in [3] will be used in this paper to analyse the stability of the DC link voltage when the load changes abruptly. The model was established in the rotating DQ frame including the dynamics of the power loops, network, and loads. The state space model has the form of

$$\dot{x} = Ax \quad (9)$$

$$x = \begin{bmatrix} \underbrace{\Delta \omega \quad \Delta \delta \quad \Delta P \quad \Delta Q \quad \Delta v_{dc} \quad \Delta i_{od} \quad \Delta i_{oq}}_{FC}, \\ \underbrace{\Delta \omega \quad \dots \quad \Delta i_{oq}}_{Battery}, \underbrace{\Delta \omega \quad \dots \quad \Delta i_{oq}}_{\mu GT}, \\ \underbrace{\Delta i_{LineD} \quad \Delta i_{LineQ} \quad \dots}_{Distribution \ lines}, \underbrace{\Delta i_{LoadD} \quad \Delta i_{LoadQ} \quad \dots}_{Loads} \end{bmatrix}^T$$

where A is the state space matrix,

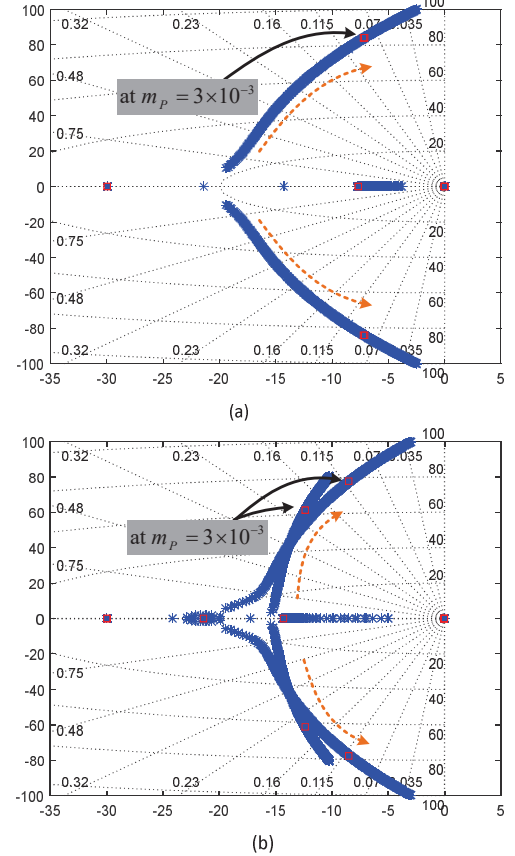


Fig. 4. Dominant system eigenvalues when $0.5 \times 10^{-4} > m_p > 5 \times 10^{-5}$ and lines inductances are (a) neglected (b) $L_{Line1} = 1mH$ and $L_{Line1} = 2mH$

As was shown from (7), the line impedance alters the locations of the designed eigenvalues and hence the damping. Fig. 4a shows the dominant eigenvalues of the microgrid when the three inverters have $1mH$ output inductance each with negligible line impedances (see Fig. 1) as m_p varies from 5×10^{-5} to 5×10^{-3} . The eigenvalues traces are identical and behave similarly. Fig. 4b shows the same traces but with different line inductances: $L_{Line1} = 1mH$ and $L_{Line1} = 2mH$. It is clear that for the same m_p range the corresponding eigenvalues represent different damping ratios. The eigenvalues when $m_p = 3 \times 10^{-3}$ are highlighted in both figures to show that the same droop gain produces different damping ratios.

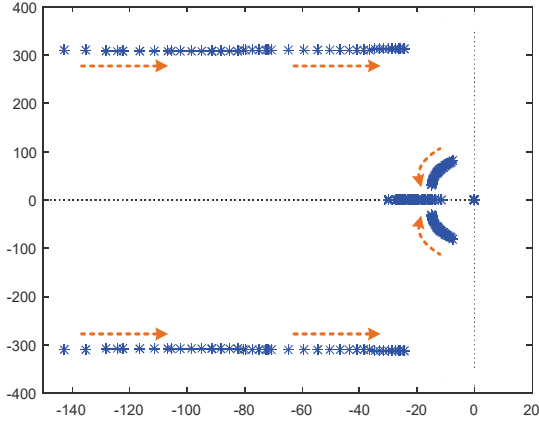


Fig. 5. System Eigenvalues when $0.5 \times 10^{-3} < L_{Line} < 5 \times 10^{-3}$

Fig. 5 shows the dominant eigenvalues when the lines inductances L_{Line1} varies from 0.5×10^{-3} to 5×10^{-3} with a ratio of 1:2 is kept between L_{Line1} and L_{Line2} and a fixed m_p value of 3×10^{-3} . Higher values of lines inductances introduce high frequency modes to the system response with lower damping; which agrees with the observation from the last section about eigenvalues migration when the output impedances change.

V. PROPOSED CONTROLLER

To limit the DC link voltage during the normal operation of a microgrid, the DC link voltage, after exceeding a triggering values, v_{tr} , will affect the frequency state which influences the active power. Fig. 6 shows the proposed control strategy.

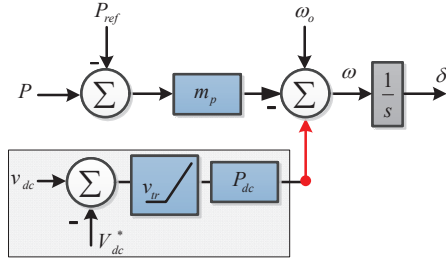


Fig. 6. Proposed controller of extra Dc link voltage loop

By analysing the control track, the small signal output frequency from (1) is derived as:

$$\Delta\omega = -m_p\Delta P + P_{dc}\Delta v_{dc}, \quad (10)$$

where Δv_{dc} is a small signal state of the DC link voltage and derived in [11] as:

$$\Delta v_{dc} = -\frac{k_{dc}}{s}\Delta p_{ins}, \quad (11)$$

where k_{dc} is the DC voltage linearizing factor and the negative sign denotes the negative flow of power direction.

By ignoring the power measurement LPF and thus assuming that the average and instantaneous powers are equal and by substituting (11) in (10) we get

$$\Delta\omega = -\left[m_p + \frac{P_{dc}k_{dc}}{s}\right]\Delta P. \quad (12)$$

Therefore, the phase state is obtained as:

$$\Delta\delta = -\left[\frac{m_p s + P_{dc}k_{dc}}{s^2}\right]\Delta P. \quad (13)$$

The new extra loop mimics an integral droop term with a gain of $P_{dc}k_{dc}$.

Table I Simulated system parameter

Symbol	Description	Value
$L_{o,i}, R_{o,i}$	Inverter output impedance	1 mH, 0.1Ω
$L_{Line,1}, R_{Line,1}$	Line 1 impedances	1 mH, 0.002Ω
$L_{Line,2}, R_{Line,2}$	Line 2 impedances	2 mH, 0.0035Ω
m_p	Frequency drooping gain	1×10^{-3} rad/s/W
n_q	Voltage drooping gain	1×10^{-3} V/Var
V_o	Voltage set point	110 Vrms
f_o	Frequency set point	50 Hz
ω_c	Measurement filter cut-off frequency	30 rad/sec
V_{DClink}^*	Nominal DC link voltage	200 V
V_{trip}	DC link trip voltage	280 V
v_{tr}	Triggering voltage level	215 V
k_{dc}	Linearization factor relating V_{DClink}^2 to V_{DClink}	2.5
C_{dclink}	DC link capacitor for ESS, μGT and PV	2000μF
P_{dc}	Proposed controller gain	0.5×10^{-3}

VI. SIMULATION RESULTS

A microgrid consisting of three inverters as shown in Fig. 1 was simulated in Matlab/SimPowerSystem to validate the performance of the proposed control scheme. The converters and inverters are represented by the ideal sources models. The simulation parameters are listed in Table I.

The DC link voltages are obtained when the load changed suddenly from 100% of 6kW to 0%. In Fig. 7, the power responses are differently damped and some power is imported. If the DC/DC converter is bi-directional as for the battery systems, it will sink the power from the DC link capacitor to maintain the voltage around the set point. However, if the DC/DC converter is unidirectional as in the systems of fuel cell and gas micro-turbines, the DC voltage can't be bounded as show in Fig. 7b.

The power and DC link voltage responses are shown in Fig. 8 with the proposed controller. It is clear that the response has been limited, which confirms the effectiveness of the proposed strategy.

VII. EXPERIMENTAL RESULTS

A single phase microgrid consisting of three DC/AC inverters and three DC/DC converters as shown in Fig.1 has been built in the lab. The energy sources are lead-acid battery bank and two fixed DC power sources representing unidirectional energy source. One of the DC/DC converters has been configured as a bidirectional converter to interface the battery while the others were configured as unidirectional boost converters. The control algorithms have been realized using OPAL-RT real time simulator. The parameters of the system and controllers are shown in Table II.

Fig. 9 shows the active power responses and the DC link voltages of the three inverters when the power of each was 200W (total load was 600W). At $t = 6$ sec the load was disconnected. During the transient, the circulating power between the inverters charged the fuel cell and micro turbine DC link capacitors. The proposed controller caped the rise in the DC link voltage and prevent any unit to shut down. The oscillation appeared for the DC link voltage response can be reduced by the controller gain. However, this might slow it down.

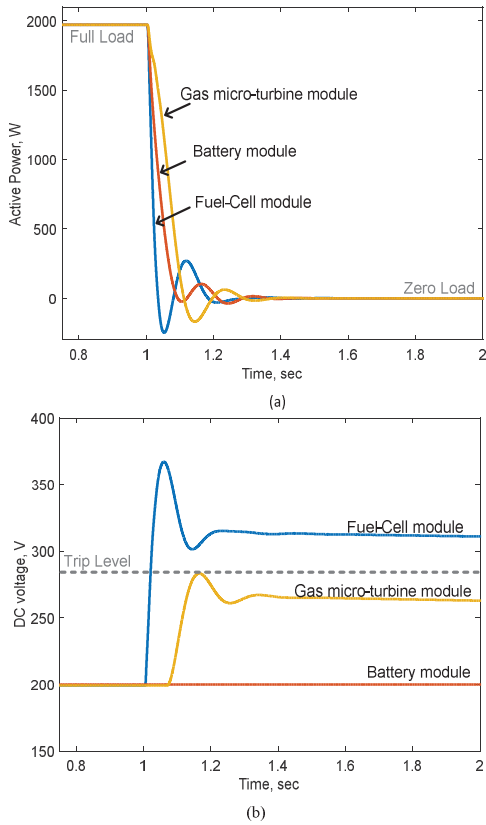


Fig. 7. Detailed simulation results of inverter's power and DC link voltage responses under load change when different distribution lines are used

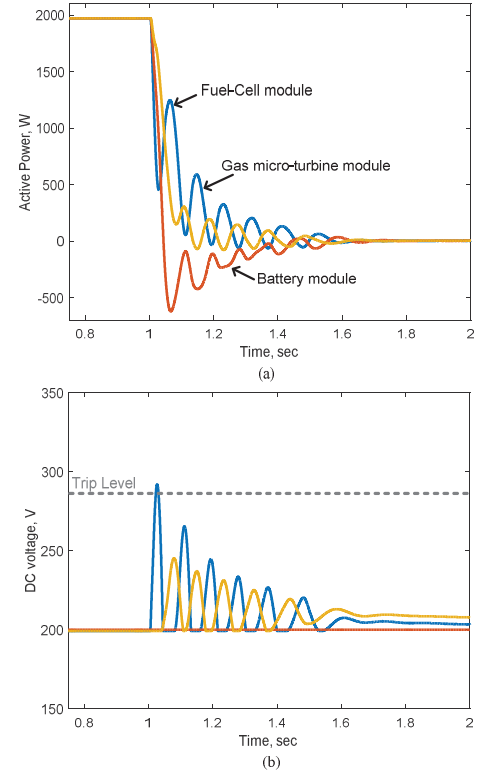


Fig. 8. Averaged power (a) and DC link voltage (b) responses

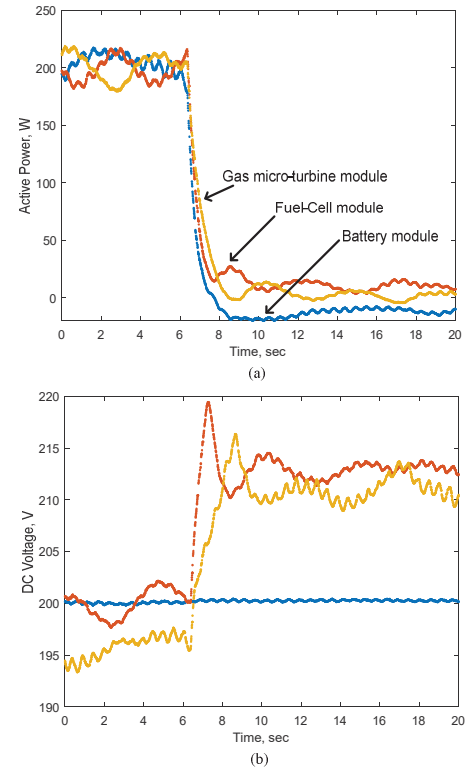


Fig. 9. Experimental results of the (a) active powers and (b) DC link voltages

Table II Experimental setup parameters

Inverters parameters		DC/DC Converters	
L_1	4mH	L_{DC}	0.8mH
C	25 μ F	V_{bat}	125V
L_2	2mH	V_{dc}	200 V
V	110 V	DC/DC current controller	
ω	2 π .50 rad/s	k_{p_c}	5 $\times 10^{-3}$
C_{dc}	1100 μ F	k_{i_c}	1
L_{line1}	1mH	DC/DC voltage controller	
L_{Line2}	2mH	k_{p_v}	20
f_{sw}	10kHz	k_{i_v}	50
Inverter voltage controller		Proposed controller	
k_v	0.01	P_{dc}	0.5 $\times 10^{-3}$
k_c	3	v_{tr}	215 V
L_v	8mH	v_{trip}	280 V
Droop controller			
m_p	1 $\times 10^{-3}$		
n_q	1 $\times 10^{-3}$		
ω_c	2 rad/s		

VIII. CONCLUSION

This paper has investigated the effect of the mismatch in line impedances on the stability of the DC link voltage during a sudden load changes. Equal droop control gains guarantee equal steady state power sharing. However, these gains don't achieve equitable transient responses, particularly, when the output impedances including the line impedances are not identical. A small signal state space model of a microgrid consisting of three inverters has been used to analyse the system. A controller scheme to control the DC link voltage during load disturbances has been proposed. The DC link voltage manipulates the output frequency to limit the imported power. The theoretical analysis and the performance of the proposed controller have been validated by simulation and experimental results.

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